ARL 62-372

COMMENTS ON THE PROBLEM OF AN OPTICAL RADAR SYSTEM

R. K. H. GEBEL

SOLID STATE PHYSICS LABORATORY

JUNE 1962

AERONAUTICAL RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE

NOTICES

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

- - - - - - - - - -

Qualified requesters may obtain copies of this report from the Armed Services Technical Information Agency, (ASTIA), Arlington Hall Station, Arlington 12, Virginia.

- - - - - - - - - -

This report has been released to the Office of Technical Services, U. S. Department of Commerce, Washington 25, D. C. for sale to the general public.

- - - - - - - - - -

Copies of ARL Technical Documentary Reports should not be returned to Aeronautical Research Laboratory unless return is required by security considerations, contractual obligations, or notices on a specific document.

ARL 62-372

COMMENTS ON THE PROBLEM OF AN OPTICAL RADAR SYSTEM

R. K. H. GEBEL

SOLID STATE PHYSICS LABORATORY

JUNE 1962

Projects 7072 and 7021
Task 70846

AERONAUTICAL RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

400 - July 1962 - 40-1756 & 1757

FOREWORD

This technical report was accomplished under Project 7072, "Research on the Quantum Nature of Light" and under Project 7021, "Solid State Research and Properties of Matter" and Task 70846, "Semiconductor Research" by R. K. H. Gebel of the Solid State Physics Research Laboratory, Aeronautical Research Laboratories, Office of Aerospace Research, United States Air Force.

The author wishes to express his sincere gratitude to Major William Lauterbach for technical review of this report. Acknowledgement is given to Mr. Roy Hayslett for assistance in the preparation of this report and to Mr. Donald C. Reynolds, Mr. Lawrence C. Greene and Mr. Hermann R. Mestwerdt for helpful discussions.

The research work on the monitor-recording system shown in Figure 2 using the xerographic principles was performed at ARL by Mr. D. C. Van Sickle.

ABSTRACT

The need for optical radar equipment is discussed. The selection of the most suitable receiving system is analyzed and calculations for the requirements concerning the radiating source for such a system are computed. The usefulness of commercially available lasers for such a system is investigated. Solid State Research providing new materials for laser-like devices is discussed.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

INTRODUCTION

The growing number of radar installations constantly increases the probability of interference between stations and it is obvious that, in the case of an emergency when nearly all stations are operating at the same time, a large percentage will encounter difficulties. Enemy radar or jamming will make the situation worse. Therefore, the need for new frequency bands and new methods usable for radar are vital. A radar system utilizing either visible light or frequencies corresponding to atmospheric windows in the near or far infrared may be quite useful. In the following the possibility of using visible light for such a purpose is analyzed.

THE TECHNICAL ARRANGEMENT

As in conventional radar three tasks are the objective of the system: image display, image recording, and distance measurement. The active source located in an airplane, produces a high powered narrow beam of light that scans the ground line by line with constant angular velocity perpendicular to the line of flight (Figure 1). Some of the light reflected from the ground, both from natural illumination and from the active source, is collected by a suitable optical system and detected by a photosensor also located in the aircraft. The photosensor should be spectrally matched to the active source to make optimum use of the radiated energy. Obviously the best resolution of the system is determined by the beam width. Since this is an active device, most of the quanta of light received should be light reflected from the area on the ground illuminated by the source located in the aircraft, and not from the areas illuminated by natural sources as, for example, the stray light of the night sky.

For the least complicated system the horizontal angle of view of the photosensor cannot be smaller than the angle of sweep of the light source. For more complex systems for optimum signal to noise ratio, the horizontal angle of view for the photosensor may be smaller; but then the photosensor would also have to sweep and the range of distance the reflected light travels should be known in order to maintain the proper angle between sweeping source and sensor and to give the photosensor sufficient angle of view corresponding to the range of distance. Then a photomultiplier tube with a small diameter photocathode or a narrow slit photocathode will be the most suitable transducer, since only one point, the individual point illuminated at the ground will reflect the light used for detection. Other photosensing devices having large area photocathodes will decrease the signal to noise ratio because of the inherent dark current and the effects of the stray light from other areas if no limiting aperture is used in the focal plane. Restricting the size of the photocathode in the photomultiplier to a minimum, determined by the image size in the focal plane of the spot illuminated on the ground, is mandatory for optimizing. In a system using a light beam for scanning, the use of an image forming photosensor, similar to that used in simultaneous or sequential light amplifier systems, would be wasteful and can hardly achieve, in this case, the same signal to noise ratio as a well designed photomultiplier. Interrupting the light source at the end of each line for a short time can be used as retrace time for the system, as well as a time base for measuring the distance and determining the end of a line. This also fixes the beginning of each line at its proper place at the recorder.

Further, the beam of the active source scanning the ground may be pulsed in order to have higher peak brightness. A gating circuit inserted between the photomultiplier and the recording device then will assure a better signal to noise ratio as a result of the reduction in the inherent dark current and the current caused by the other areas on the ground. However, the distance has to be known in order to pulse the photosensor at the right time. The correct gating may be determined by a pulse position discriminator working with another non-pulsed photosensor which may be similar to an automatic frequency control in a television set. The original pulses used for the active source then produce a saw tooth signal, which is employed for time comparison with the pulses from the non-pulsed photosensor, resulting in distance indication.

The minimum vertical angle of view of the photosensor will be determined by the width of the beam of the active source, the speed of the aircraft and the distance involved. However, in very sophisticated systems compensation for the speed is possible and the aperture for the photosensor may be determined by the size of the spot of light from the source as reflected from the ground. Obviously, if a system is built where the cone of the angle of view of a scanning photosensor corresponds to one resolution spot, and if reflection from natural illumination is intense enough, an image will be obtained without the active source.

The reflected light received at the photosensor is converted to a sequential electrical signal, due to the scanning actions described above. This signal may then be used for producing an image for direct visual observation or written down for storage, line by line, by magnetic tape, xerographic methods, storage CRT, etc.

If it is desired to have a continuous view of the ground, two storage reproducer tubes could be used sequentially; during the time that one is displaying, the other can store line by line until the full number of lines necessary for display of a whole image is stored. Another attractive method giving an endless permanent record would be the direct recording on a band with xerographic methods as seen in Figure 2. Further, a reproducer tube which has a storage screen in the form of a moving drum is conceivable as a solution for a continuous viewing device, then the pilot can see on the tube a display which would be similar to direct viewing.

THE RESOLUTION

The number of lines L scanned by the system per second should be adapted to the aircraft speed V in meters per second, the altitude A in meters of the aircraft, and to the effective cone angle α in radians with which the active source radiates so that each line of illumination on the ground will be adjacent to the next one. For vertical reconnaissance, it is

$$L = \frac{V}{\alpha A} = \frac{V}{R} \tag{1}$$

where

$$R = \alpha A \tag{2}$$

is the width in meters of one line of scan on the ground and also the diameter of one resolution element.

If for vertical operation, t_L is the time in seconds necessary to sweep the angle β corresponding to one line of scan, t_r is the time in seconds for the light to return to the vehicle, and δ is the angle in radians between the radiating beam of the active source and the axis of the beam of light detected by the photosensor,

then

$$\delta = \frac{t_R}{t_L}\beta \approx \frac{2A\beta}{3\times10^8 t_L} \tag{3}$$

Since α is a given value, the value chosen for β determines the effective number of horizontal resolution elements n_r per line. It is

$$n_R \approx \frac{D}{R} \approx \frac{\beta}{\alpha} \tag{4}$$

where D is the length of a line of scan on the ground.

Example 1: An optical radar system is used in an aircraft flying at 750 meters per second; $\alpha = 10^{-2}$ radians, A = 1000 meters, β = 1 radian. We find by Eq(2)

$$R = 10^{-2} \times 10^3 = 10 \text{ meters}$$

and using Eq(1)

$$L = \frac{750}{10} = 75 \text{ lines per second}$$

and using Eq(4)

$$n_R \approx \frac{1}{10^{-2}} = 100 \text{ resolution elements per line}$$

and assuming continuous scanning, that is $t_L = \frac{1}{L}$, by using (Eq(3),

$$\delta = \frac{2\times1000\times1\times75}{3\times10^8} \approx 5\times10^{-4}$$

This value is too small to be considered and the photosensor, if also scanning the ground, is practically in the same angular position as the transmitting beam of light.

REQUIREMENTS CONCERNING THE LIGHT SOURCE

The light transmitted from the active source in a cone with an angle α is diffusely reflected at the ground and only a very small fraction of this light can be collected by the optical system and detected by the photosensor. An approximation for the attenuation factor K which is the ratio of the emitted number of quanta Q_E to the received number of quanta Q_R may be calculated. For simplicity, since many different situations exist, it is assumed that all photons

emitted by the active source are equally reflected by the ground over the half sphere with the area $2\ \pi A^2$ then

$$K = \frac{Q_E}{Q_R} \approx \frac{2\pi A^2}{\frac{\pi d_a^2}{4}} \approx 8\left(\frac{A}{d_a}\right)^2 \qquad (7)$$

where d_a is the diameter of the aperture in the optical system used for collecting the reflected light. If the efficiency factor by which the ground reflects the light (albedo) is expressed by η_G, the efficiency of the optical system by η_O and the quantum efficiency of the transducer by η_a, the attenuation factor K_{eff} expressing the ratio between the number of emitted photons to the number of electrons produced by the photosensor becomes:

$$K'_{eff} \approx \frac{K}{\eta_G\ \eta_O\ \eta_a} \qquad (8)$$

Then the most favorable signal to noise ratio S attainable under ideal conditions, usually assumed to be determined by a Poisson distribution, is

$$S = \left(\frac{Q_E}{K'_{eff}}\right)^{\frac{1}{2}} \qquad (9)$$

The active light source has to be pulsed to measure the distance as in any other radar system. The time interval t_i in seconds between pulses must be at least as long as the pulse duration t_p plus the time required for the light to travel the greatest distance ℓ in meters which is being measured. Then for t_i we find

$$t_i > \left(t_p + \frac{2\ \ell_{max}}{3 \times 10^8}\right) \qquad (10)$$

The pulse duration t_p has to be shorter than the time required for the light to travel the least distance to be measured.

$$t_p < \frac{2\ \ell_{min}}{3 \times 10^8} \qquad (11)$$

t_p should be in the microsecond range for all practical purposes. For an image display system the minimum number of pulses P_{min} for each line and therefore

the number of resolution elements necessary to just cover practically all of the area of a line of scan on the ground should be

$$p_{min} = \frac{\beta}{\alpha} \tag{12}$$

and the minimum number of pulses P'_{min} per second becomes

$$p'_{min} = p_m L \tag{13}$$

Example 2: A commercially available laser emitting a cone of light (λ 6943A°) with a half value beam divergence of less than 30 minutes of arc delivers a nominal power P_L per pulse of 3×10^8 ergs and can produce up to 6 pulses per minute. The pulse duration t_p is about 1 milli-second and maximum intensity is reached after 3 microseconds. In the following these values will be used to determine the feasibility of using such a laser fulfilling the conditions as in Example 1. The number of photons Q_E produced by the laser is

$$Q_E = \frac{P_L}{h \frac{c}{\lambda}} \tag{14}$$

In this case

$$Q_E = \frac{3 \times 10^8}{6.625 \times 10^{-27} \times \frac{3 \times 10^8}{0.6943 \times 10^{-6}}} \approx 10^{20}$$

In the previous example 75 lines per second were scanned which would result in a line time of $\approx$ 13 milli-seconds. However, since the laser produces a pulse duration t_p of 1 milli-second only, the scanning of one line has to be done during this one milli-second and then the unit would be blanked during the next 12 milli-seconds to prevent over lapping of the scanned area. Achieving the scan in one milli-second by mechanical means may present some difficulties. Further, since the laser quoted in this example can produce only 1 pulse every 16 seconds a prohibitively large number of lasers of this kind working sequentially would be necessary.

The attenuation factor for Example 1, using Eq(7), utilizing an optical system of 8 inch diameter and $\eta_G = 0.1$, $\eta_0 = 0.5$, $\eta_p = 0.1$ is

$$K = \frac{8\left(\frac{1000}{0.2}\right)^2}{0.1 \times 0.5 \times 0.1} = 4 \times 10^{10}$$

and the number of electrons E_p obtained from the photon flux during the effective time one resolution element is illuminated may be approximated to be

$$E_p \approx \frac{Q_E}{K} \frac{\alpha}{\beta} \tag{15}$$

This is in our case

$$E_p = \frac{10^{20}}{4 \times 10^{10}} \times \frac{10^{-2}}{1} = 2.5 \times 10^7$$

which is more than sufficient for a good signal to noise ratio. Therefore, a laser producing one pulse every 10 milli-seconds with an intensity of 10^{16} instead of one pulse with 10^{20} photons every 10 seconds would be a usable solution, since only one laser would then be needed instead of an impossibly large number as previously indicated.

However, the particular commercially available laser as in Example 2 could be used successfully with a light intensifier imaging device. Then several hundred lines would be illuminated at once, instead of scanning line by line. Since 1 foot candle of sunlight (λ 415 to 670 mμ) is about 10^{17} photons per square meter per second and neglecting the sun's color temperature, an area of 1000 by 1000 meters iluminated with 10^{20} photons would correspond to about 10^{-3} foot candle illumination over a second of time. This is about thirty times the value of the illumination as provided by the night sky and should be enough to provide a good signal to noise ratio. In such a mode of operation then light intensifier devices of the sequential as well as simultaneous type could be successfully used; the sequential system with a storage reproducer, and the simultaneous type by

employing between the photocathode and reproducing phosphor a storage grid similar to the ones used in storage CRT's.

In that mode of operation whereby a large area is flooded with light, a pulse duration of one micro-second would be preferable to the one milli-second pulse duration quoted for the commercially available laser. This shorter pulse duration would permit simple instrumentation for distance measurements; for instance with a storage grid image convertor with a calibrated delay line system for pulsing at the proper time.

The narrow spectral spread of the light from a laser can only be used to its full advantage if the photosensor used has an identical spectral sensitivity characteristic. This is usually not the case for photocathodes in imaging devices. The use of light sources for the above purpose other than the present ruby lasers should be investigated, especially those capable of producing a single pulse of extremely short time duration at a precisely determined time.

At the Aeronautical Research Laboratories, cadmium sulfide crystals have been grown by D. C. Reynolds and L. C. Greene, which can be excited to emit visible light with a photon energy of about 2.39 eV. The initial energy necessary to produce this light is obtained by two separate steps; first, by radiation with a photon energy of about 1.8 eV and then by radiation with a photon energy of about 0.75 eV. However, the initial energy furnished to the crystal by the radiation of 1.8 eV photon-energy may also be supplied by raising the crystal temperature to about 300°K and then cooling to liquid nitrogen temperature. The energy supplied by the radiation with a photon energy of 0.75 eV may be replaced by mechanical shock.

If crystals of such behavior could be used in a laser-like device it would have enormous advantages, compared to the ruby laser, which must be supplied with a radiation having a photon energy higher than the energy of the emitted photons. Since most ruby lasers have a conversion efficiency which is only of the order of 0.3% the energy needed presents a big problem.

The phenomena observed at ARL in these crystals might be explained by the simplified energy band model of Figure 3. To produce the above mentioned behavior, the cooled crystal (77°K) is flooded with radiation having a photon energy of at least 1.78 but less than 2.53 eV. This raises electrons from the donor level to the conduction band, but the energy is not sufficient to raise any from the valence band to the conduction band. The electrons that have been removed from the donor level leave holes, where some of the holes may be filled during the flooding process by electrons coming from lower regions of the valence band. Electrons brought to the conduction band drop to the edge emission level, until this level is filled. The edge emission level, trapping the electrons, does not contribute to the electrical conductivity of the crystal, but if the edge emission level is filled, the surplus of electrons remains in the conduction band. This produces the behavior that has been called stored conductivity. If now the crystal is flooded with radiation having a photon energy of about 0.75 eV, electrons are raised from the valence band to fill the holes in the donor level, leaving holes in the valence band. These holes recombine with the trapped electrons from the edge emission level, causing the emission of light with about 2.39 eV photon-energy (green light 5200°A). In the case of the mechanical excitation one may assume that, the holes from the donor level fall to the valence band,

because of this excitation, making the recombination of the trapped electrons from the edge emission level possible.

The intensity of the emission rises to the maximum in 2×10^{-7} seconds and then has decayed after another 8×10^{-7} seconds to 1/e. The band width of the main emission is about 10 A° and about 10^6 photons per mm^3 are released. Since similar effects have been observed in zinc sulfide crystals, it may be hoped that further research may lead to crystals with sufficient light output to make feasible laser-like devices that are more useful for many purposes than the present ruby laser. They should provide in contrast to the ruby laser shorter pulse times, the capability to produce one single pulse at an arbitrary precisely determined time and conversion from low energy photons to high energy photons.

BIBLIOGRAPHY

1. Gebel, R. K. H., and Devol, L., The Limiting Detectivity of Optical Amplifying Equipment, Z. Instr. 69 (1961) Heft 10, p. 271 to 276, Heft 11 p. 296 to 299.

2. Greene, L. C., Reynolds, D. C., Czyzak, S. J., and Baker, W. M., "Method for Growing Large CdS and ZnS Single Crystals", J. of Chem. Phys. Dec. 1958.

3. Litton, C. W., and Reynolds, D. C., "Edge Emission in CdS Crystals that Show Mechanically Excited Emission", Phys. Rev., Jan. 1962.

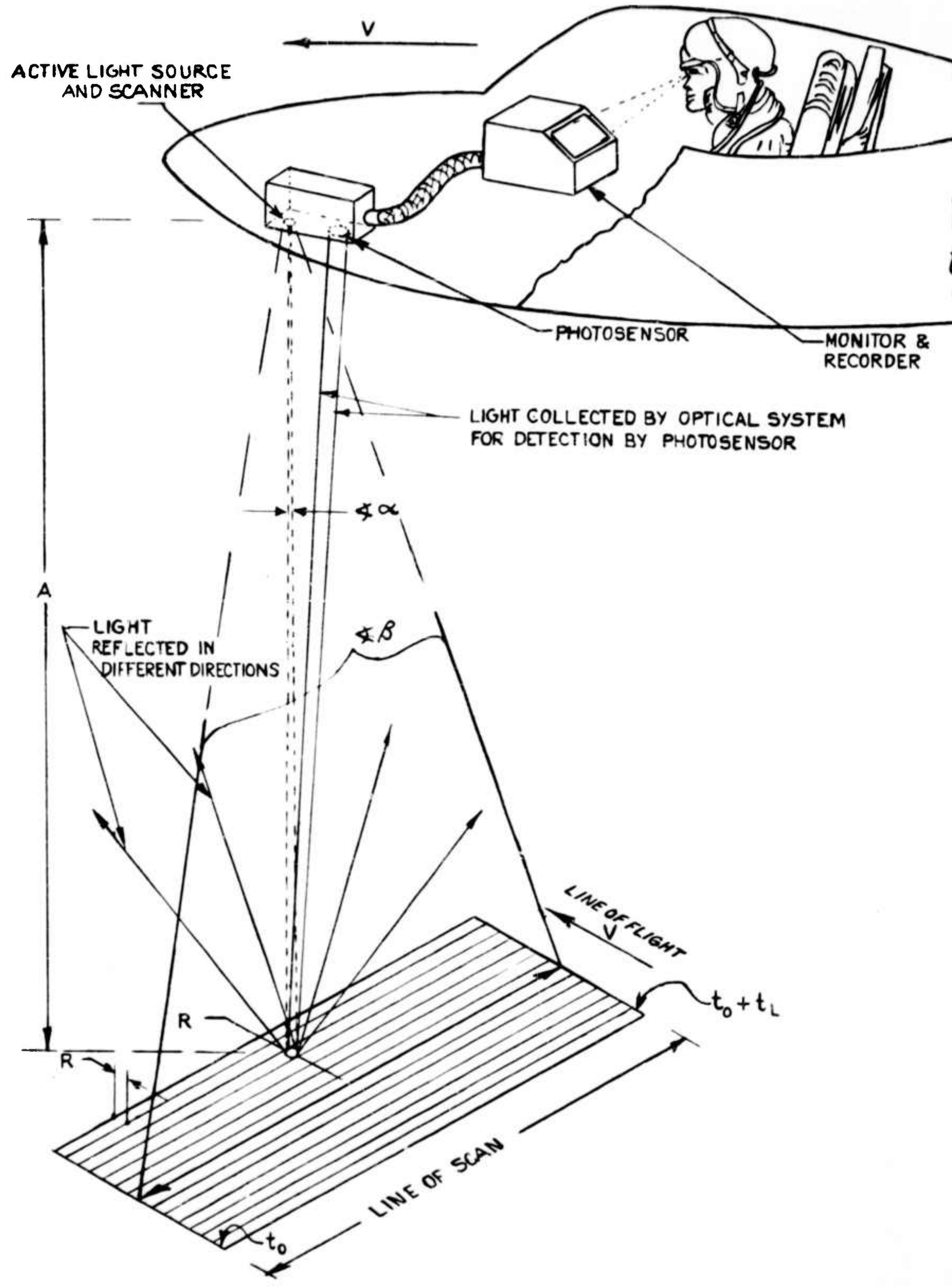

Figure 1. Optical Radar System

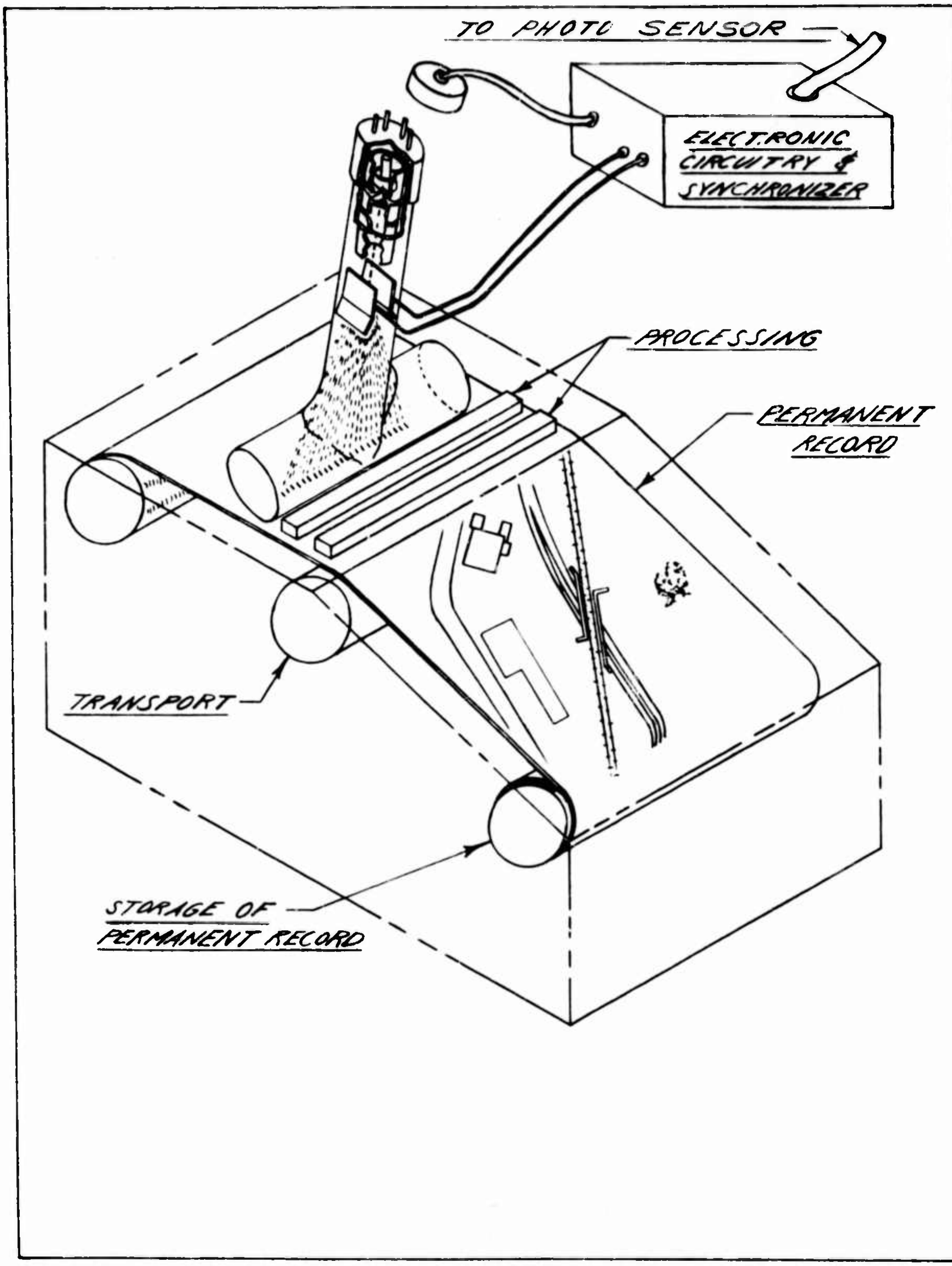

Figure 2. Monitor and Recorder

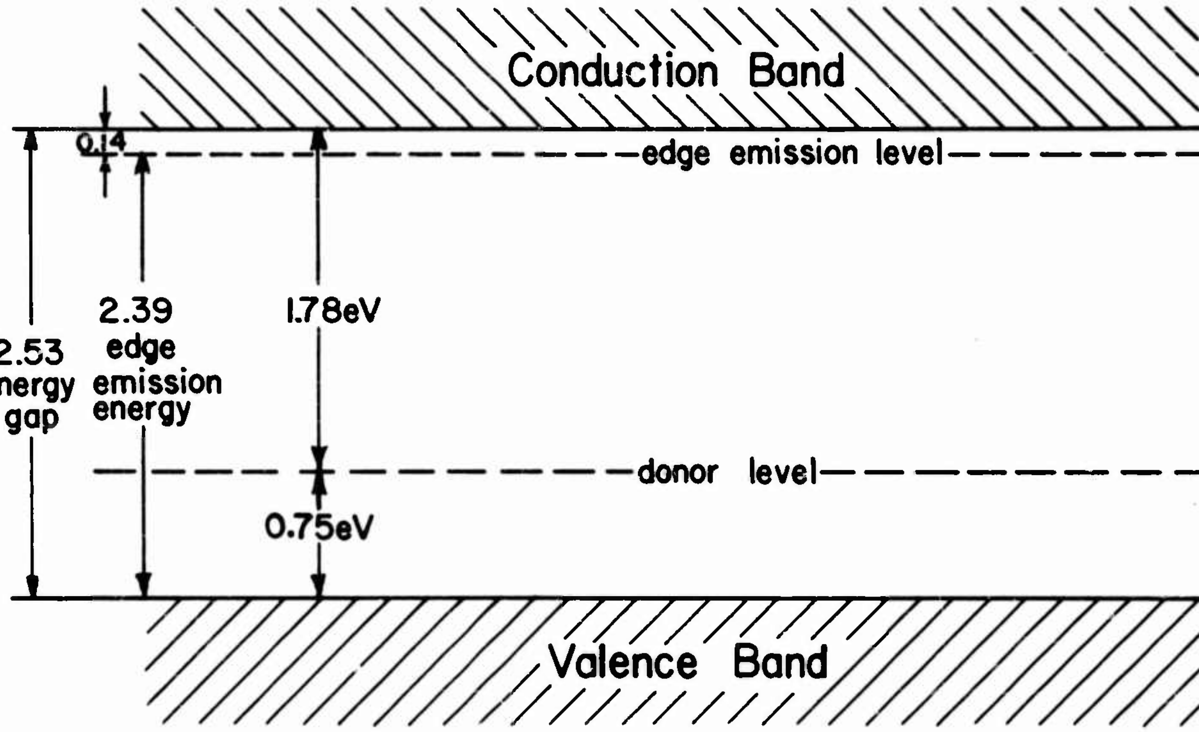

Figure 3. Simplified Working Model of CdS Storage Crystals with Donor Level

Aeronautical Research Laboratories, Wright Patterson AFB, Ohio. COMMENTS ON THE PROBLEM OF AN OPTICAL RADAR SYSTEM by R. K. H. Gebel, Solid State Physics Lab., ARL. June 1962. 13 p. incl. illus. (Projects 7072 and 7021; Task 70846) (ARL 62-372) Unclassified Report

The need for optical radar equipment is discussed. The selection of the most suitable receiving system is analyzed and calculations for the requirements concerning the radiating source for such a system are computed. The usefulness of commercially available lasers for su

(over)

UNCLASSIFIED

UNCLASSIFIED

cially available lasers for such a system is investigated. Solid State Research providing new materials for laser-like devices is discussed.

UNCLASSIFIED

UNCLASSIFIED

Aeronautical Research Laboratories, Wright Patterson AFB, Ohio. COMMENTS ON THE PROBLEM OF AN OPTICAL RADAR SYSTEM by R. K. H. Gebel, Solid State Physics Lab., ARL. June 1962. 13 p. incl. illus. (Projects 7072 and 7021; Task 70846) (ARL 62-372) Unclassified Report

The need for optical radar equipment is discussed. The selection of the most suitable receiving system is analyzed and calculations for the requirements concerning the radiating source for such a system are computed. The usefulness of commercially available lasers for su

(over)

UNCLASSIFIED

UNCLASSIFIED

cially available lasers for such a system is investigated. Solid State Research providing new materials for laser-like devices is discussed.

UNCLASSIFIED

UNCLASSIFIED

Aeronautical Research Laboratories, Wright Patterson AFB, Ohio. COMMENTS ON THE PROBLEM OF AN OPTICAL RADAR SYSTEM by R. K. H. Gebel, Solid State Physics Lab., ARL. June 1962. 13 p. incl. illus. (Projects 7072 and 7021; Task 70846) (ARL 62-372) Unclassified Report

UNCLASSIFIED

The need for optical radar equipment is discussed. The selection of the most suitable receiving system is analyzed and calculations for the requirements concerning the radiating source for such a system are computed. The usefulness of commercially available lasers for su

(over)

UNCLASSIFIED

UNCLASSIFIED

cially available lasers for such a system is investigated. Solid State Research providing new materials for laser-like devices is discussed.

UNCLASSIFIED

Aeronautical Research Laboratories, Wright Patterson AFB, Ohio. COMMENTS ON THE PROBLEM OF AN OPTICAL RADAR SYSTEM by R. K. H. Gebel, Solid State Physics Lab., ARL. June 1962. 13 p. incl. illus. (Projects 7072 and 7021; Task 70846) (ARL 62-372) Unclassified Report

UNCLASSIFIED

The need for optical radar equipment is discussed. The selection of the most suitable receiving system is analyzed and calculations for the requirements concerning the radiating source for such a system are computed. The usefulness of commercially available lasers for su

(over)

UNCLASSIFIED

UNCLASSIFIED

cially available lasers for such a system is investigated. Solid State Research providing new materials for laser-like devices is discussed.

UNCLASSIFIED

Aeronautical Research Laboratories, Wright Patterson AFB, Ohio. COMMENTS ON THE PROBLEM OF AN OPTICAL RADAR SYSTEM by R. K. H. Gebel, Solid State Physics Lab., ARL. June 1962. 13 p. incl. illus. (Projects 7072 and 7021; Task 70846) (ARL 62-372) Unclassified Report

The need for optical radar equipment is discussed. The selection of the most suitable receiving system is analyzed and calculations for the requirements concerning the radiating source for such a system are computed. The usefulness of commercially available lasers for su

(over)

UNCLASSIFIED

UNCLASSIFIED

cially available lasers for such a system is investigated. Solid State Research providing new materials for laser-like devices is discussed.

UNCLASSIFIED

UNCLASSIFIED

Aeronautical Research Laboratories, Wright Patterson AFB, Ohio. COMMENTS ON THE PROBLEM OF AN OPTICAL RADAR SYSTEM by R. K. H. Gebel, Solid State Physics Lab., ARL. June 1962. 13 p. incl. illus. (Projects 7072 and 7021; Task 70846) (ARL 62-372) Unclassified Report

The need for optical radar equipment is discussed. The selection of the most suitable receiving system is analyzed and calculations for the requirements concerning the radiating source for such a system are computed. The usefulness of commercially available lasers for su

(over)

UNCLASSIFIED

UNCLASSIFIED

cially available lasers for such a system is investigated. Solid State Research providing new materials for laser-like devices is discussed.

UNCLASSIFIED

UNCLASSIFIED

Aeronautical Research Laboratories, Wright Patterson AFB, Ohio. COMMENTS ON THE PROBLEM OF AN OPTICAL RADAR SYSTEM by R. K. H. Gebel, Solid State Physics Lab., ARL. June 1962. 13 p. incl. illus. (Projects 7072 and 7021; Task 70846) (ARL 62-372) Unclassified Report

The need for optical radar equipment is discussed. The selection of the most suitable receiving system is analyzed and calculations for the requirements concerning the radiating source for such a system are computed. The usefulness of commercially available lasers for su

(over)

UNCLASSIFIED

UNCLASSIFIED

cially available lasers for such a system is investigated. Solid State Research providing new materials for laser-like devices is discussed.

UNCLASSIFIED

UNCLASSIFIED

Aeronautical Research Laboratories, Wright Patterson AFB, Ohio. COMMENTS ON THE PROBLEM OF AN OPTICAL RADAR SYSTEM by R. K. H. Gebel, Solid State Physics Lab., ARL. June 1962. 13 p. incl. illus. (Projects 7072 and 7021; Task 70846) (ARL 62-372) Unclassified Report

The need for optical radar equipment is discussed. The selection of the most suitable receiving system is analyzed and calculations for the requirements concerning the radiating source for such a system are computed. The usefulness of commercially available lasers for su

(over)

UNCLASSIFIED

UNCLASSIFIED

cially available lasers for such a system is investigated. Solid State Research providing new materials for laser-like devices is discussed.

UNCLASSIFIED

UNCLASSIFIED